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When oil and water mix: Understanding the environmental impacts of shale development

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ABSTRACT

Development of shale gas and tight oil, or unconventional oil and gas (UOG), has dramatically increased domestic energy production in the U.S. UOG resources are typically developed through the use of hydraulic fracturing, which creates high-permeability flow paths into large volumes of tight rocks to provide a means for hydrocarbons to move to a wellbore. This process uses significant volumes of water, sand, and chemicals, raising concerns about risks to the environment and to human health. Researchers in various disciplines have been working to make UOG development more efficient, and to better understand the risks to air quality, water quality, landscapes, human health, and ecosystems. Risks to air include releases of methane, carbon dioxide, volatile organic compounds, and particulate matter. Water-resource risks include excessive withdrawals, stray gas in drinking-water aquifers, and surface spills of fluids or chemicals. Landscapes can be significantly altered by the infrastructure installed to support large drilling platforms and associated equipment. Exposure routes, fate and transport, and toxicology of chemicals used in the hydraulic fracturing process are poorly understood, as are the potential effects on terrestrial and aquatic ecosystems and human health. This is made all the more difficult by an adaptable and evolving industry that frequently changes methods and constantly introduces new chemicals. Geoscientists responding to questions about the risks of UOG should refer to recent, rigorous scientific research.

INTRODUCTION

Large-scale scientific and engineering investigations into the natural gas potential of organic-rich shales began after the 1973–1974 OPEC oil embargo (Soeder, 2017). The Eastern Gas Shales Project (EGSP) was funded from 1977 to 1992 by the U.S. Department of Energy (DOE) with the goal of adapting engineered hydraulic fracturing treatments, also known as "fracking,"[1] to create flowpaths from natural fracture networks within the shales to vertical wellbores. The EGSP field experiments showed that fracking alone was insufficient to produce economical amounts of hydrocarbons from vertical wells (Soeder, 2017).

By the mid-1990s, technical advances in directional drilling for deep-water oil and gas, along with improvements in downhole bit navigation (Rao, 2012), enabled Mitchell Energy to bore long, horizontal wells called "laterals" into the Barnett Shale in the Fort Worth Basin of Texas. These laterals, which contacted a much greater volume of the shale formation than vertical wells, were stimulated with a series of staged hydraulic fractures carefully spaced into discrete zones along the lateral. The combination of horizontal drilling and staged hydraulic fracturing resulted in the production of economical quantities of natural gas from the Barnett Shale, initiating modern shale-gas and tight-oil development (Soeder, 2017). Most estimates suggest that many decades of energy supplies are available from unconventional oil and gas (UOG) resources at current usage rates (USGS, 2015).

The commercial development of shale gas and tight oil requires drilling, fracking, production, and transmission of oil/gas, management of waste streams, and well-closure (Fig. 1 #1–7) (USEPA, 2016). The scale of development has raised questions about possible risks to air, water, landscapes, ecosystems, and human health (Soeder and Kappel, 2009; Soeder et al., 2014). Large drill rigs (Data Repository Fig. S1[2]) are required to install the long, deep laterals. The land-clearing and pad construction activities needed to accommodate such equipment often modify landscapes and watersheds (Fig. 1 #10). Fracking involves injection of large volumes of water (~0.1 to >10 million liters) with sand to prop the fractures open and chemical additives such as friction reducers, corrosion inhibitors, anti-scale agents, and biocides (USEPA, 2016; https://fracfocus.org/). The water, sand, and additives are pumped into wells under pressures that exceed rock-strength to create fractures (Figs. 1 #3–4 and S2 [see footnote 2]). Many of the risks at each step of UOG development are known while others remain poorly understood (Table S1 [see

GSA Today, v. 28, https://doi.org/10.1130.GSATG361A.1.

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[1] The term "frack" (with the k) is commonly used by shale gas opponents ("fracktivists") in reference to the entire drilling, stimulation, and production process. Proponents use the spelling "frac" (minus the k) in reference only to the stimulation step. The word has no standard spelling, but for phonetics and consistency with similar words (e.g., crack) we have chosen to include the "k" but limit the use to the stimulation process.

[2] GSA Data Repository Item 2018251, six tables and eight figures with supporting information, is online at www.geosociety.org/datarepository/2018/.

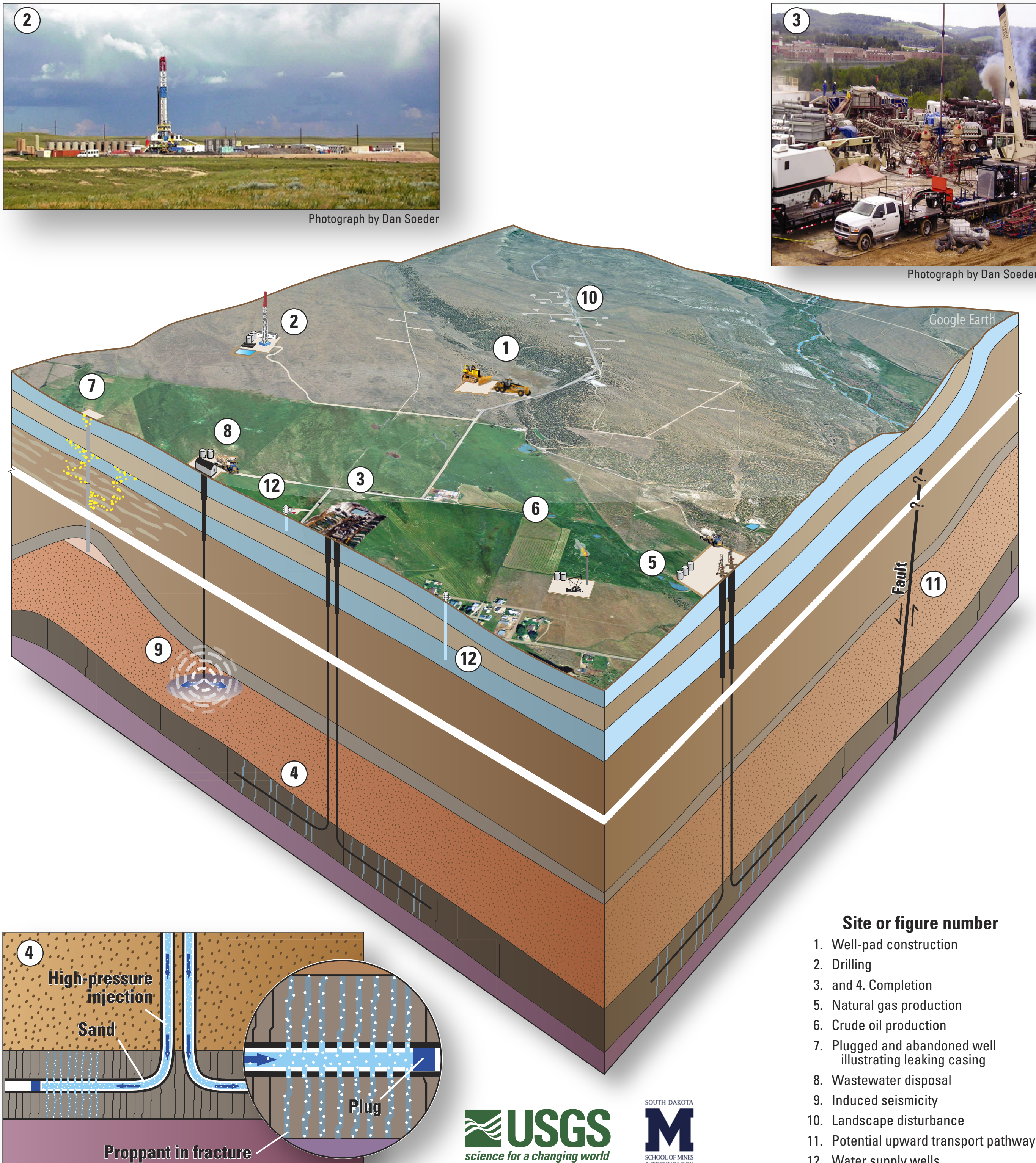

Figure 1. Schematic diagram illustrating unconventional oil and gas (UOG) development activities relevant to research on human-health and environmental impacts (not to scale): well-pad construction (1); drilling (2); completion/stimulation (3, 4); production of natural gas (5) and oil (6) with well casings designed to protect drinking-water aquifers; ultimate closure (plug and abandon), illustrating legacy well with leaking casing (7); wastewater disposal (8); induced seismicity (9); landscape disturbance (10); and potential for transport pathways from deep to shallow formations (11). Also represented are water supply wells in shallow and deep aquifers (12). Photographs by Dan Soeder.

footnote 2]), and the overall combined risk is difficult to assess (Rodak and Silliman, 2012). For example, of 1606 chemicals identified in wastewater from UOG wells, chronic toxicity values are only available for 173 (USEPA, 2016). The United States will continue to rely on the production of fossil fuel hydrocarbons for some time (Fig. S3 [see footnote 2]), and understanding of the risks must be improved.

Researchers at government agencies, universities, institutes, and industry have been investigating potential human-health and environmental impacts of UOG development. Herein we use "environmental impacts" to refer to impacts on aquatic and terrestrial organisms, communities, and ecosystems. This article aims to highlight the critical research questions in this area and to provide access to results of ongoing research.

RESEARCH QUESTIONS AND PRIORITIES

The Health Effects Institute in Boston, Massachusetts, conducted an exhaustive review of the scientific literature and solicited expert advice to identify the research needed to reduce uncertainty about potential human-health and environmental-impact risks from UOG development (HEI, 2015), identifying thirteen critical research areas (Table S1).

Assessing human-health impacts from UOG operations is complicated and challenging. A typical approach combines toxicology data with measurements of chemical exposure. Shale development sites have multiple stressors that may be detrimental to human health in nearby communities, such as chemical stress from produced-water spills, physical stress from airborne particulate matter, sensory stress from the noise and light, and emotional stress from traffic and equipment. Geoscientists play a critical role in identifying possible exposure routes of potentially hazardous materials.

The U.S. Department of the Interior (DOI), Environmental Protection Agency (EPA), and DOE developed a collaborative research framework for assessing risk from UOG development. The Department of Health and Human Services (HHS) was engaged for human-health issues, and the National Science Foundation (NSF) was engaged to coordinate federal research with academic research (Multiagency, 2014).

Seven priority research areas were identified: (1) domestic UOG resource development trends to identify potential future impacts; (2) effects of hydraulic fracturing water consumption on local and regional water availability; (3) potential water-quality degradation from UOG development and linkage of contaminants to UOG activity; (4) potential short- and long-term air-quality impairments; (5) induced seismicity from fracking and liquid waste disposal in underground injection control (UIC) wells; (6) potential impacts of UOG development on terrestrial and aquatic ecosystems; and (7) possible effects of UOG development on human health. Lead roles in these seven areas were given to agencies based on core capabilities and mission (U.S. DOE, 2015) (Fig. S4 [see footnote 2]).

DOE research focused on engineering investigations of how drilling fluids, hydraulic fracturing chemicals, and produced liquids and gas may escape from wellbores, tanks, and other containments and enter the environment (e.g., Fig. S5 [see footnote 2]). Studies include wellbore integrity and cement technology (Kutchko et al., 2012); fate and transport of frack chemicals in groundwater (Soeder et al., 2014); and the potential for greenhouse gas (GHG) releases (Pekney et al., 2014). Field research sites have been established by DOE in West Virginia, Texas, Louisiana, and Virginia.

DOI research has primarily been performed by the U.S. Geological Survey (USGS) to assess technically recoverable UOG resources (e.g., USGS, 2015), understand the chemical composition of produced and formation waters (e.g., Orem et al., 2014; Blondes et al., 2017), and compile data related to water used for hydraulic fracturing (e.g., Gallegos et al., 2015). Water quality upstream and downstream from oil and gas wastewater injection and pipeline spill sites has been assessed (Fig. 1 #8) (e.g., Akob et al., 2016; Cozzarelli et al., 2017), along with impacts on wildlife driven by UOG-related modifications to landscapes (e.g., Preston and Kim, 2016; USGS, 2017). Induced seismicity, which results primarily from the disposal of produced water down UIC wells (Fig. 1 #9) (Rubinstein and Mahani, 2015), was investigated under the USGS earthquake hazards program.

EPA research has focused on documenting risks and identifying knowledge gaps regarding impacts of UOG development on drinking-water sources (USEPA, 2016). The EPA is also engaged in the induced seismicity issue because the agency is responsible for regulating UIC wells.

An NSF-supported study of the linkages and relationships between agriculture, energy, and water resources on the northern Great Plains investigated a concept called the food-energy-water (FEW) nexus. This area contains just 1% of the U.S. population, yet it produces 23% of the nation's crop value and 16% of U.S. energy. Scarce water resources are heavily used for both agriculture and energy, and tipping points were identified that could prevent recovery of water resources. Thus, sustainable water management practices are critical (Sieverding and Jones, 2015).

RESEARCH TO ADDRESS POTENTIAL AIR- AND WATER-QUALITY IMPACTS OF UOG DEVELOPMENT

Airborne pollutants from UOG development include methane (CH_4), carbon dioxide (CO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM) released during well pad construction, drilling (Figs. S5 and S6 [see footnote 2]), hydraulic fracturing (Fig. S2), returned-fluids handling, and production (Fig. S7 [see footnote 2]). VOCs and NO_x directly degrade local and regional air quality and can form ground-level ozone and particulate matter. Variations in the composition and scale of air emissions complicate characterization of UOG sites. Automated collection and analysis of air samples obtained with mobile laboratories provide inputs for atmospheric fate and transport models (Pekney et al., 2014). Methane leakage from gas wells contributes to GHG emissions, and although it has a shorter residence time in the atmosphere compared to CO_2, CH_4 is a much more powerful GHG. On the other hand, abundant natural gas from shale has resulted in the replacement of many old, coal-fired power plants with natural gas-fired generation, significantly decreasing CO_2 emissions from electricity production (USEIA, 2017) and improving air quality (Mac Kinnon et al., 2018).

Stray methane gas is the most common groundwater problem in areas of Marcellus Shale development in Pennsylvania, followed by dissolved salts from produced water (Brantley et al., 2014). Other contaminants linked to shale gas include metals, naturally occurring radioactive materials (NORM), and organic compounds. Contaminants enter surface water primarily through spills or leaks and infiltrate downward into shallow aquifers. No evidence supports aquifer contamination by the upwelling of fluids from production zones (e.g., Fisher and Warpinski, 2012; Hammack et al., 2014; McMahon et al., 2017).

Recent investigations have contributed to a growing consensus that stray gas in aquifers results primarily from casing failures in older production wells, rather than migration from zones where hydraulic fracturing was conducted in horizontal wells (e.g., Brantley et al., 2014; Lackey et al., 2017). The challenges of understanding stray gas migration in the subsurface were illustrated by a test at the Borden groundwater research site in Ontario, Canada. Methane was injected into the well-characterized, shallow sand aquifer, and migration was monitored spatially and temporally at high resolution (Cahill et al., 2017). The gas was transported in solution by advection and diffusion and laterally in the gas phase through interconnected layers of somewhat coarser sediments (Fig. 1 #7). It persisted in the aquifer for more than a year, longer than expected.

Baseline water-quality data are needed to assess potential water-quality degradation. Researchers from the USGS and Northeast Midwest Institute investigated decades of legacy water-quality data from the Susquehanna River Basin in Pennsylvania to determine if baseline conditions prior to shale-gas development could be determined (Betanzo et al., 2016). Most of the existing water-quality monitoring sites were found in the lower parts of the basin and established for nutrient and pesticide inputs to the Chesapeake Bay. The data sets were not useful for assessing water-quality impacts of shale-gas development in headwater streams. Impacts of UOG development on groundwater and surface-water quality can be difficult to distinguish from impacts of septic systems and legacy coal mining (Messinger and Hughes, 2000), but elemental ratios and isotopic compositions can provide signatures of wastewater from UOG production (e.g., Akob et al., 2016; Lauer et al., 2016; McMahon et al., 2017).

Residential water-supply wells in the vicinity of new oil and gas production wells are often sampled to provide pre-drilling information about water quality. The data are collected for liability reasons (USEPA, 2016) and are not well suited for interpreting sources of contamination (Table S2 [see footnote 2]). Molofsky et al. (2016) assessed best practices for sampling, laboratory analysis methods, data management, and analysis protocols for residential water wells in areas of UOG development.

RESEARCH TO ADDRESS POTENTIAL IMPACTS OF LIQUID AND SOLID WASTES AND SPILLS

Increases in UOG activities result in more environmental violations (Kell, 2011) and spills (Lauer et al., 2016). An 11.3-million-liter spill of Bakken and Three Forks produced water into a North Dakota creek contained total dissolved solids (TDS) of 300 g per liter and high concentrations of ammonium, barium, strontium, and radium (Lauer et al., 2016; Cozzarelli et al., 2017). Geochemical alterations in the stream persisted for at least six months after the spill, and fish kills were observed 7 km downstream of the spill site. Radium and strontium isotopic signatures in downstream sediments resembled those from the spilled fluid (Cozzarelli et al., 2017). Slow release of spill-derived chemicals from sediment could provide a long-term contaminant source in aquatic ecosystems.

Organic-rich shales were deposited in anoxic marine environments and contain sulfide minerals, radionuclides, and reduced inorganic elements (Chermak and Schreiber, 2014). Hydraulic fracturing fluids often react with shale downhole, mobilizing inorganic compounds like barium (Renock et al., 2016) or creating new organic compounds that are found in the produced fluids (Kahrilas et al., 2016).

Horizontal drilling of a single shale well can generate several hundred tons of drill cuttings, which may release harmful elements like arsenic, radium, and uranium (Phan et al., 2015). The leachability of drill cuttings has been investigated in the laboratory under short-term and long-term exposures and different environmental conditions, resulting in the identification of potentially toxic metals being mobilized from black-shale drill-cuttings (e.g., Stuckman et al., 2015). Understanding these processes will guide management of these waste materials.

SITE-BASED PROJECTS EXAMINING POTENTIAL ENVIRONMENTAL IMPACTS OF UOG DEVELOPMENT

Access to UOG sites for environmental monitoring has been challenging for non-industry researchers (Soeder, 2015), but collaboration between academic, government, and industry researchers has been improving. A multidisciplinary project begun in 2013 to examine potential environmental and human-health impacts of UOG development, primarily in the Rocky Mountain region (Table S3 [see footnote 2]), has produced more than 50 publications assessing air- and water-quality impacts; wastewater treatment and re-use; public health outcomes; and socio-political and economic factors associated with UOG development. Potential water-resource risks have been assessed near Marcellus Shale wells in Susquehanna County, Pennsylvania, since 2015 (Table S4 [see footnote 2]). Analyses of produced water and hydrocarbons from production wells are providing signatures for potential contaminants like trace metals, major ions, and hydrocarbons. Studies like these will provide insight into the natural spatial and temporal variation in water quality needed to detect impacts from UOG development.

Field research projects involving partnerships between DOE and industry are improving UOG-development technologies while reducing environmental and health impacts. The Hydraulic Fracturing Test Site (HFTS) in the Permian basin of Texas underwent environmental assessments before, during, and after development phases (Fig. 1 #1–6). Air quality was monitored for methane, NO_x, and VOCs. Groundwater quality was monitored within 4 km of production wells. Produced water was analyzed to evaluate potential impacts to wellhead and casing integrity (Table S5 [see footnote 2]). New hydraulic fracturing technologies were tested to optimize hydrocarbon extraction efficiency. Preliminary findings indicate that groundwater quality was not degraded by the activity onsite; final results will be published in a DOE report.

The Marcellus Shale Energy and Environment Laboratory (MSEEL) is a long-term, collaborative field site located near Morgantown, West Virginia, to develop and validate new technology for improving recovery efficiency and reducing environmental impacts of shale-gas development (Table S6 [see footnote 2]). The MSEEL developed a geologic and engineering baseline using two older Marcellus wells at the site, and a vertical drill core of the Marcellus Shale was obtained from one of the new production wells. A scientific observation well supplied detailed subsurface information including 150 sidewall cores and provided monitoring access for new hydraulic fracturing technologies tested in the production laterals, which also furnish produced water and gas samples to researchers. Quality of surface water, air, and noise were monitored by geochemists, health professionals, and social scientists. Continued research at MSEEL is expected to improve extraction and management of subsurface energy resources and advance scientific understanding of the environmental and social impacts of shale development.

These two field sites have been joined more recently by the Eagle Ford Shale Laboratory in Texas, the Tuscaloosa Marine Shale Laboratory (TMSL) in Louisiana, and the Field Laboratory for Emerging Stacked Unconventional Plays (ESUP) in the Nora Gas Field in Virginia. The Geological Survey of Canada also has been performing field investigations of potential hydrocarbon migration from the Utica Shale at a depth of 2 km to shallow aquifers in the St. Lawrence lowlands (Rivard et al., 2016). Variable isotopic compositions of CH_4 indicate that biogenic and thermogenic methane likely originated from black shales underlying shallow bedrock aquifers. Although upward migration of deep brine was discovered along a normal fault, there is no evidence of significant gas migration from the Utica Shale.

ALTERNATIVE MATERIALS AND PRACTICES

A study at the University of Arkansas, Little Rock, assessed industry adoption of hydraulic fracturing technologies that use "greener" chemicals, including low-VOC and food-based compounds and geosynthetics to enhance containment (Thomas et al., 2018). Environmental risks of standard frack fluid chemicals and green alternatives need to be better understood, and the oil and gas industry must be convinced that green chemicals perform as well as and cost the same or less than the chemicals they replace.

These issues are also being addressed by the Environmentally Friendly Drilling (EFD) program supported by DOE at the Houston Advanced Research Center (HARC). Field trials of new technologies for site selection, drilling, completion, production, and gas compression, along with public perception studies, help industry develop oil and gas resources in a more environmentally responsible manner.

CHALLENGES AND OPPORTUNITIES

Research on the environmental impacts of UOG development was affected by dramatic decreases in oil and gas prices beginning in 2014 (Fig. S8 [see footnote 2]). Natural gas prices fell first, leading to a steady decline in the number of active drill rigs on the shale gas plays, followed a few months later by a significant drop in oil prices, leading to an even more abrupt decline in the number of active rigs drilling the Bakken Shale (USEIA, 2016). These changes resulted in logistical challenges or cancellations of planned field-monitoring projects as drillers shifted to the more lucrative parts of a play (e.g., Soeder, 2015). Fewer operating drill rigs reduced the number of potential access options for investigators.

Oil and gas production is a cyclical business. Unconventional resources feed the same markets as all other components of the energy sector. During boom times, industry is in a frenzy to gain lease positions and install wells while prices are high and competition stiff. Partnering in research on environmental and human-health impacts is low on their priority list. When prices drop, development slows down. There is less drilling and fewer opportunities for researchers, but the downward part of the cycle also provides an opportunity to discuss potential partnerships in projects investigating environmental and human-health impacts. Industry partners are more willing to listen to researchers' ideas and interested in data that could increase efficiency, reduce uncertainty, facilitate fact-based regulations, and improve their social license to operate (Table S6).

Geoscientists are frequently called upon to answer questions about fracking. The issues are neither simple nor static, and keeping up with rapidly evolving technology and a highly adaptable industry is a significant challenge. For example, in 2010, the discharge of high TDS wastewater in the effluent from municipal wastewater treatment plants was identified as the greatest environmental risk from UOG development (Rozell and Reaven, 2012). Beneficial use of produced water for road de-icing and dust suppression (e.g., Skalak et al., 2014) was curtailed. A few years later, water management practices had changed to flowback recycling and disposal of residual waste down UIC wells (Rodriguez and Soeder, 2015), eliminating worries about discharge from wastewater plants. These were replaced by new concerns over the risk of spills or leaks from the improper handling of produced water (e.g., Patterson et al., 2017), and high volumes of wastewater injection causing induced seismicity (Llenos and Michael, 2013). In conclusion, the public is concerned about the uncertainties of human-health and possible environmental risks of fracking, which geoscientists can address through rigorous scientific research and responsible public engagement (Brantley et al., 2018).

ACKNOWLEDGMENTS

This article grew out of a Pardee Symposium convened at the 2016 GSA Annual Meeting in Denver, Colorado, USA, where researchers from academia, industry, and government discussed progress toward understanding the environmental impacts of UOG development. We gratefully acknowledge support for the symposium provided by the Pardee Symposium Fund of the Geological Society of America. Funding for the authors was provided by the U.S. DOE National Energy Technology Laboratory, the USGS Toxic Substances Hydrology Program, and the USGS Water Mission Area. Joe Gardiner (USGS) produced Figure 1. Comments by Mike Focazio, Isabelle Cozzarelli, Mark Engle, Christopher Conaway, Barbara Bekins, Joe Ryan, Gerald Dickens, and three anonymous reviewers greatly improved the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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Manuscript received 3 Feb. 2018
Revised manuscript received 25 May 2018
Manuscript accepted 28 May 2018